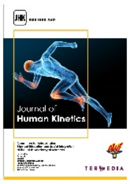

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Section III – Sports and Physical Activity

Effects of Three Resistance Strength Training Methods on the Biomechanics and Kinematics of the Lower Limbs during the First Step of Sprinters' Start

by

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This study aimed to compare the effects of three distinct resistance training methods, i.e., complex strength training (CST), plyometric training with additional loading (PT), and eccentric training (ET), on lower-limb biomechanics in the sagittal plane and on performance during the first step after pushing off the starting block. This study assessed the effects of the training protocols on sprint acceleration performance and muscular explosiveness in sprinters over an 8-week intervention period. Twenty-four male sprinters, with personal best times ranging from 11.00 to 11.70 s, were randomly assigned to one of the three groups: CST, PT or ET. Each group completed an 8-week training intervention. Kinematic and kinetic data for the first step off the starting block were synchronously collected using an infrared motion-capture system and force plates. The results indicated that CST was more effective than both PT and ET in enhancing step frequency, peak ground reaction force, lower-limb joint torque, and joint stiffness during the first step in sprinters. Accordingly, CST interventions may be particularly beneficial for improving sprint starts. These findings highlight the need for further long-term intervention studies to explore this potential in greater depth.

***Keywords**: joint stiffness; strength training; acceleration phase; sprint start; joint mechanics*

Introduction

The acceleration phase at the start of a sprint is vital to the performance of elite 100-m sprinters (Bezodis et al., 2010). Moreover, performance during the push-off from the starting block and subsequent strides is closely related to 100-m race times (Bezodis et al., 2014). After the initial push-off, the velocity of the center of mass during the first step is the highest among all ground contact phases. In this phase, the ground reaction force (GRF) generated by the interaction between the lower limbs and the ground propels the sprinter forward in the shortest possible time. High-level sprinters exhibit a higher rate of force development, producing greater net propulsive impulses that translate into higher velocities and greater displacement of the center of mass. Given its critical importance, the acceleration phase has been extensively studied to better understand the biomechanics of the first-step ground contact. Previous research has examined external kinetics, joint kinematics, joint kinetics, horizontal velocity of the centre of mass, and segmental energy to determine their effects on performance (Bezodis et al., 2013, 2014; Jérémy et al., 2025; Otsuka et al., 2014; Slawinski et al., 2010).

Analyzing the biomechanical characteristics of the lower limbs during this phase provides valuable insights into the factors that influence performance and musculoskeletal demands associated with specific movements. Such research typically focuses on joint stiffness, joint torque, and GRF. Joint stiffness reflects the stability and resistance to deformation provided by joint structures, such as bones, ligaments, tendons,

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and muscles, when subjected to external forces. Joint torque is the product of the force acting on a joint and its lever arm, describing the extent to which this force influences joint rotation. GRF refers to the force exerted by the ground on the contact points of the human body or an object, acting as a counterbalancing mechanism to maintain equilibrium and facilitate both vertical and horizontal movements.

In sports, sprinting performance is closely related to the level of explosive strength. Targeted strength training has been shown to substantially enhance lower-limb explosiveness (Cormie et al., 2010; Herman et al., 2008). Plyometric training with additional loading (PT) primarily enhances lower-limb strength and explosiveness by improving the stiffness of the lower limbs, hips, and ankles (Jing and Liu, 2010). Both plyometric and traditional strength training methods improve explosiveness, and combining these two modalities into complex strength training (CST) has been shown to yield superior improvements in neuromuscular control compared with either method alone (Herman et al., 2008). Additionally, eccentric training (ET) has been found to enhance explosiveness and joint stiffness in athletes performing technical movements (Jing and Liu, 2010; Wang et al., 2017), with ET producing notably higher eccentric peak torque than concentric training.

In summary, CST, PT, and ET have all been shown to improve lower-limb explosiveness and joint stiffness. However, the differences among CST, PT, and ET in terms of joint stiffness, joint torque, and GRF during the starting acceleration phase remain unclear and require further investigation. Therefore, this study focused on male sprinters and aimed to determine the effects of different strength training methods on the biomechanics and muscular explosiveness of the sprint-start acceleration phase. Furthermore, the study investigated the biomechanical factors of the lower-limb joints that influence performance at the start of a sprint.

Methods

Participants

Twenty-four young male sprinters participated in this study. The sample size was determined using G*Power (version 3.1.9.4) based on a repeated-measures analysis of variance model. The following variables were applied: an estimated effect size of 0.04 (η^2), an alpha level of 0.05, statistical power of 0.80, three groups, two repeated measurements, a within-group correlation coefficient of 0, and a non-sphericity correction factor of 1. The calculation indicated that each group required a minimum of eight participants, resulting in a total sample of 24 (age: 20.2 ± 0.8 years; body mass: 61.8 ± 9.3 kg; body height: 1.72 ± 0.05 m; best 100-m sprint performance: 11.35 ± 0.32 s). All participants were free from lower-limb musculoskeletal injuries during the six months preceding the study. They were randomly assigned to one of the three groups: CST (n = 8), PT (n = 8) or ET (n = 8).

Ethical approval was obtained from the Institutional Review Board of the Hunan Normal University, Changsha, China (approval code: 581; approval date: 20 December 2022). Before the commencement of the study, participants were fully informed about the study aim, procedures, potential risks and benefits. Written informed consent was obtained from all participants before data collection started.

Instrumentation

Sprint start experiments were conducted on an indoor track (Figure 1). A three-dimensional motion analysis system (Qualisys, Sweden) equipped with eight cameras recorded motion data at a sampling rate of 200 Hz. Twenty-nine reflective markers were placed on anatomical landmarks of each participant, including the top, anterior, and posterior regions of the head, the right scapula offset, the fifth lumbar vertebra, the acromion processes, the lateral humeral epicondyles, midpoints of the radial and ulnar styloid processes, anterior thighs, lateral and medial femoral epicondyles, tibial tuberosities, medial and lateral malleoli, toes, and heels. Two embedded force plates (Kistler 9281EA, Switzerland; 40 × 60 cm each) were positioned in front of the starting blocks to collect GRF data at a sampling frequency of 1000 Hz. To maintain consistency and prevent participants from deliberately targeting the plates, their surfaces were covered with the same material as the track.

Training Methods

In compound (complex) training, each paired training method was performed for 2–5 sets. Athletes completed 1–5 repetitions of strength exercises and 5–15 repetitions of rapid-contraction compound exercises. Alternatively, training intensity could be set at 85% for strength exercises and 75% for explosive power exercises. Most previous studies have used resistance loads >85% of one-repetition maximum (1RM) for strength training (Dugan et al., 2004). Eccentric loading refers to the resistance encountered by muscles at the onset of contraction, which limits muscle shortening. Performing lower-limb hyperextension exercises with a 30% 1RM load allows muscles to produce maximum strength at their optimal initial length and achieve optimal power output, particularly maximal explosive power, due to the effective application of eccentric loading (Carter and Greenwood, 2014). When performing eccentric strength training, the load intensity must exceed that used in concentric training, typically ranging from 120% to 150% of the maximum concentric load. The duration of eccentric contractions should be at least twice that of concentric contractions (Wang and Liu, 2014).

All participants trained twice per week, with at least 48 h between sessions. Approximately 15 min after each training session, participants completed a session rating of perceived exertion (s-RPE) to ensure balanced training loads among groups. Throughout the study, participants were instructed to refrain from any additional lower-limb strength training outside the experimental protocol. All three groups followed identical training schedules.

Procedures

Participants wore standardized athletic shorts and spiked shoes. They completed a warm-up routine and familiarized themselves with the experimental conditions.

Testing was conducted as follows: participants performed a maximum-effort sprint start by pushing off from the starting blocks and running a distance of 30 m. A trial was considered successful if it met all of the following criteria: no false starts, the first step landing within the designated area of the force plate, and no marker loss during data collection. To minimize fatigue, participants were given adequate rest between trials and completed three successful attempts each.

Linear and angular kinematics of the joints and segments were calculated from the smoothed coordinate data. Ankle and knee joint moments were subsequently derived from the GRF, kinematic variables, the center of mass location, and segmental inertia properties. Joint stiffness was computed as the slope of the linear approximation of the net joint moment relative to the decrease in the joint angle during the support phase. The foot strike and toe-off during sprinting were determined using the vertical GRF with a threshold of 10 N (Rabita et al., 2015), and the subsequent contralateral foot strike was visually identified using high-speed camera footage. The peak GRF was defined as the maximum GRF observed during the landing phase, and the peak GRF time was the time at which this maximum occurred. Filtered GRF data were used to calculate peak force during the buffering (GRF1) and push-off (GRF2) phases. GRF1 peak time referred to the time at which GRF peaked during the buffering phase, and GRF2 peak time referred to the time at which GRF peaked during the push-off phase. The time to reach the 30-m mark was defined as the duration from the start signal to the moment the horizontal position reached the designated mark. Step length was defined as the distance between the toes in the running direction from the ipsilateral (left leg) foot strike to the subsequent contralateral foot strike. Step frequency was defined as the inverse of step duration from the ipsilateral foot strike to the subsequent contralateral foot strike. Support time referred to the duration from the foot strike to toe-off, while flight time was the duration from toe-off to the subsequent foot strike. Joint power was calculated as the product of joint moment and joint angular velocity. Positive and negative joint power phases were identified, with joint work calculated by integrating power-time curves using the trapezium rule. Positive work (energy generation) and negative work (energy absorption) were defined accordingly. Hip and knee joint extension and ankle joint plantarflexion were considered positive. All joint data (except angles) and external powers were normalized to dimensionless values to allow comparisons between athletes (Bezodis et al., 2010; Hof, 1996). The whole-body center of the mass position was calculated using Visual3D.

Sprint performance is predominantly determined by the stride rate and stride length. Bret et al. (2002) emphasized the importance of lower-limb muscle strength and stiffness in the

100-m sprint. The GRF is the principal external force affecting running speed, as it is the only force, aside from gravity, that enables human acceleration or deceleration when air resistance is neglected. Therefore, a comprehensive analysis of these indicators is essential.

Statistical Analyses

Data were summarized and analyzed using Microsoft Excel 2016 and IBM SPSS Statistics version 20.0 (IBM Corp., Armonk, NY, USA). A two-way mixed-design analysis of variance [3 × 2: training intervention (CST, PT, or ET) × time (pre- vs. post-training)] was conducted to examine the effects of the different resistance training methods on the biomechanical characteristics of the lower limbs during the first step of the sprint start. Time was treated as a repeated measure, while group and time were independent variables. Kinematic and kinetic data served as dependent variables. When a significant interaction between a training group and time was found, simple main effects were analyzed. When significant main effects were identified, Bonferroni post hoc tests were performed. Effect size was quantified using eta squared (η^2), which represents the proportion of variance in the dependent variable explained by categorical predictors.

Results

The training load was controlled from both objective and subjective perspectives. The heart rate was monitored, and subjective fatigue was assessed using the s-RPE scale. The s-RPE scores for the strength training methods were as follows: CST, 2187.5 ± 137.7; PT, 2250.0 ± 185.4; and ET, 2287.5 ± 180.5. No significant differences were observed among groups ($p > 0.05$), indicating that training loads were consistent across protocols.

Significant interaction effects between training and grouping were observed for the 30-m sprint time ($p = 0.003$, $\eta^2 = 0.419$), first-step total time ($p = 0.001$, $\eta^2 = 0.826$), and first-step ground contact time ($p < 0.001$, $\eta^2 = 0.636$). Training exhibited consistent main effects across all measures ($p < 0.001$; 30-m sprint time, $\eta^2 = 0.830$; $p = 0.027$, first-step length, $\eta^2 = 0.382$; $p = 0.015$, first-step flight time, $\eta^2 = 0.352$; $p < 0.001$, first-step ground contact time, $\eta^2 = 0.636$; $p = 0.016$, first-step total time, $\eta^2 = 0.830$), whereas grouping effects were measure-dependent, with significance for the 30-m sprint time ($p < 0.001$, $\eta^2 = 0.669$) and first-step total time ($p < 0.001$, $\eta^2 = 0.622$), but not for the first-step length ($p = 0.739$, $\eta^2 = 0.075$) or first-step flight time ($p = 0.650$, $\eta^2 = 0.876$). Following the intervention, the CST and PT groups generally outperformed the ET group in the 30-m sprint time ($p < 0.001$ for both) and first-step total time (CST, $p < 0.001$; PT, $p = 0.020$). However, the CST group had significantly shorter first-step length ($p = 0.036$) and significantly shorter first-step flight time than the ET group ($p = 0.048$). No significant pre-test differences were found in most measures; however, post-test differences emerged consistently, with CST and PT groups often showing relative advantages over the ET group.

Significant interaction effects were observed between training and grouping for both the maximum hip joint torque ($p < 0.001$, $\eta^2 = 0.497$) and maximum ankle joint torque ($p = 0.025$, $\eta^2 = 0.396$). Training and grouping both exhibited significant main effects across measures, with training effects being consistent (hip, $p < 0.001$, $\eta^2 = 0.737$; ankle, $p = 0.003$, $\eta^2 = 0.556$) and grouping effects significant (hip, $p < 0.001$, $\eta^2 = 0.895$; ankle, $p = 0.040$, $\eta^2 = 0.365$). For the hip joint torque, no pre-test group differences were found (F = 0.193, $p = 0.577$, $\eta^2 = 0.072$); however, significant post-test differences emerged (F = 18.202, $p < 0.001$, $\eta^2 = 0.634$). Training effects were significant in all groups (CST, F = 17.281, $p < 0.001$, $\eta^2 = 0.451$; PT, F = 109.289, $p < 0.001$, $\eta^2 = 0.839$; ET, F = 72.291, $p < 0.001$, $\eta^2 = 0.775$). After the intervention, the CST group exhibited greater maximum hip joint torque than both the PT ($p = 0.022$) and ET ($p < 0.001$) groups, and the PT group also showed greater hip joint torque than the ET group ($p = 0.037$). In contrast, for the ankle joint torque, training effects were significant only in the CST group (F = 19.217, $p < 0.001$, $\eta^2 = 0.478$), and no significant effects were found in the PT (F = 0.925, $p = 0.347$, $\eta^2 = 0.042$) or the ET (F = 0.308, $p = 0.585$, $\eta^2 = 0.014$) group. After the intervention, the CST group had significantly higher hip joint torque than the PT group ($p = 0.015$), whereas no significant differences were found between the other groups ($p = 0.225$, $p = 0.506$).

Significant interaction effects between training and grouping were observed for both the ankle joint positive work ($p = 0.009$, $\eta^2 = 0.559$) and hip joint negative work ($p = 0.009$, $\eta^2 = 0.406$), and both training and grouping showed independent main effects. Shared patterns included significant post-test differences for both measures (ankle, F = 5.773, $p = 0.010$, $\eta^2 = 0.355$; hip, F = 8.701, $p = 0.002$, $\eta^2 = 0.453$) and consistent training benefits across groups for the hip joint negative work. Notable differences emerged: the CST group demonstrated greater ankle joint positive work than the ET group after the intervention ($p = 0.012$), whereas the ET group demonstrated greater hip joint negative work than both the CST and PT groups before the intervention ($p < 0.001$ for both); however, the CST and PT groups surpassed the ET group after the intervention ($p = 0.002$, $p = 0.039$). The knee joint's negative work exhibited the strongest interaction effect ($p < 0.001$, $\eta^2 = 0.557$), with training effects significant in the CST (F = 25.911, $p < 0.001$, $\eta^2 = 0.552$) and PT (F = 26.298, $p < 0.001$, $\eta^2 = 0.556$) groups, but not in the ET group (F = 1.396, $p = 0.251$, $\eta^2 = 0.062$). Before the intervention, the ET group demonstrated greater knee joint negative work than both the CST and PT groups ($p = 0.001$, $p = 0.006$); however, after the intervention, PT had significantly higher knee joint negative work than both the CST and ET groups ($p = 0.035$, $p < 0.001$).

Significant interaction effects were observed between training and grouping for hip ($p = 0.026$, $\eta^2 = 0.695$), knee ($p < 0.001$, $\eta^2 = 0.580$), and ankle ($p < 0.001$, $\eta^2 = 0.191$) joint stiffness. Training and grouping exhibited independent main effects across measures, with training effects reaching significance for ankle ($p = 0.025$, $\eta^2 = 0.162$) and knee ($p = 0.032$, $\eta^2 = 0.150$) stiffness and grouping effects being significant for hip ($p = 0.036$, $\eta^2 = 0.039$) and knee ($p = 0.032$, $\eta^2 = 0.150$) stiffness. For hip joint stiffness, no significant training effects were observed in any group (CST, F = 3.221, $p = 0.087$, $\eta^2 = 0.133$; PT, F = 1.664, $p = 0.211$, $\eta^2 = 0.073$; ET, F = 4.240, $p = 0.052$, $\eta^2 = 0.168$). Multiple comparisons showed the CST group had significantly higher hip joint stiffness than the ET group before the intervention ($p = 0.022$), whereas the ET group had significantly higher hip joint stiffness than the PT group after the intervention ($p = 0.023$). For knee joint stiffness, training effects were significant in the PT (F = 19.233, $p < 0.001$, $\eta^2 = 0.478$) and ET (F = 10.422, $p = 0.004$, $\eta^2 = 0.322$) groups, but not in the CST group (F = 0.617, $p = 0.441$, $\eta^2 = 0.029$). Multiple comparisons revealed that the PT group had significantly higher knee joint stiffness than both the CST and ET groups before the intervention ($p = 0.040$, $p = 0.004$), whereas the ET group had significantly higher knee joint stiffness than both the CST and PT groups after the intervention ($p = 0.003$, $p = 0.001$). For ankle joint stiffness, training effects were significant in the CST (F = 17.106, $p = 0.004$, $\eta^2 = 0.853$) and PT (F = 8.224, $p = 0.016$, $\eta^2 = 0.611$) groups, but not in the ET group (F = 1.677, $p = 0.209$, $\eta^2 = 0.074$). Multiple comparisons showed that the CST group had significantly higher ankle joint stiffness than the ET group after the intervention ($p = 0.011$), with no significant differences between the other groups ($p = 0.260$, $p = 0.459$).

Significant interaction effects between training and grouping were observed for vGRF1 ($p = 0.043$, $\eta^2 = 0.343$), vGRF2 ($p = 0.006$, $\eta^2 = 0.494$), and apGRF ($p = 0.019$, $\eta^2 = 0.391$). Shared patterns included substantial main effects of grouping for vGRF1 ($p = 0.006$, $\eta^2 = 0.500$) and vGRF2 ($p = 0.026$, $\eta^2 = 0.519$) and significant training main effects for apGRF ($p = 0.031$, $\eta^2 = 0.421$). For vGRF1, training effects were significant only in the ET group (F = 5.810, $p = 0.029$, $\eta^2 = 0.279$), with no significant effects in the CST group (F = 0.267, $p = 0.613$, $\eta^2 = 0.017$) or the PT group (F = 2.401, $p = 0.142$, $\eta^2 = 0.138$). Multiple comparisons showed that the PT group had significantly lower vGRF1 than both the CST and ET groups before the intervention ($p = 0.062$, $p = 0.002$); however, no significant differences were found after the intervention ($p = 0.567$, $p = 0.371$, $p = 0.445$). For vGRF2, training effects were significant in the CST (F = 6.871, $p = 0.019$, $\eta^2 = 0.314$) and ET (F = 7.462, $p = 0.015$, $\eta^2 = 0.332$) groups, but not in the PT group (F = 0.579, $p = 0.459$, $\eta^2 = 0.037$). After the intervention, the CST group demonstrated significantly higher vGRF2 than the ET group ($p = 0.011$), with no significant differences between the other groups ($p = 0.667$, $p = 0.143$). For apGRF, training effects were significant in all groups (CST, F = 6.871, $p = 0.008$, $\eta^2 = 0.414$; PT, F = 6.579, $p = 0.029$, $\eta^2 = 0.537$; ET, F = 7.462, $p = 0.015$, $\eta^2 = 0.332$). After the intervention, the CST group demonstrated significantly higher apGRF than both the PT ($p = 0.023$) and ET ($p = 0.032$) groups, whereas no significant difference was found between the PT and ET groups ($p = 0.511$).

The three interventions significantly reduced the 30-m sprint time. Among the groups, the CST group demonstrated greater improvement in first-step length, first-step flight time, first-step total time, lower limb joint torque during the first step, lower limb joint stiffness during the first step, and GRF compared to the PT and ET groups.

Table 1. Descriptive characteristics of the training program performed across three groups.

WK	CST				PT				TE			
	Exercise	Sets × reps	%1RM	Interval (min)	Exercise	Sets × reps	%1RM	Interval (min)	Exercise	Sets × reps	%1RM	Interval (min)
1	Half squat and a hurdle jump	6 × 5/4 × 10	85	2/6/2	Loaded CMJ	4 × 8	30	2	Half squat	5 × 6	120	2
2	Half squat and a hurdle jump	6 × 5/4 × 10	85	2/6/2	Loaded CMJ	4 × 8	30	2	Half squat	5 × 6	120	2
3	Half squat and a hurdle jump	6 × 5/4 × 10	85	2/6/2	Loaded CMJ	4 × 8	30	2	Half squat	5 × 6	120	2
4	Half squat and a hurdle jump	6 × 5/4 × 10	85	2/6/2	Loaded CMJ	4 × 8	30	2	Half squat	5 × 6	120	2
5	Half squat and a hurdle jump	6 × 5/4 × 10	90	2/6/2	Loaded CMJ	4 × 8	40	2	Half squat	5 × 6	130	2
6	Half squat and a hurdle jump	6 × 5/4 × 10	90	2/6/2	Loaded CMJ	4 × 8	40	2	Half squat	5 × 6	130	2
7	Half squat and a hurdle jump	6 × 5/4 × 10	90	2/6/2	Loaded CMJ	4 × 8	40	2	Half squat	5 × 6	130	2
8	Half squat and a hurdle jump	6 × 5/4 × 10	90	2/6/2	Loaded CMJ	4 × 8	40	2	Half squat	5 × 6	130	2

CST = complex strength training; PT = plyometric training; ET = eccentric training; %1RM = percentage of one-repetition maximum; WK = week; Sets × reps = sets × repetitions; Loaded CMJ = countermovement jump with an additional load; Half squat = thighs positioned at a 45° angle to the ground; Hurdle jump = jump over a hurdle with both feet; Interval = time interval between sets

Table 2. Differences in performance indicators among different intervention groups.

Metrics	CST (n = 8)		PT (n = 8)		ET (n = 8)		Group * Test session interaction effect
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	
30-m time (s)	4.065 ± 0.282	3.835 ± 0.225**●●	4.053 ± 0.258	3.858 ± 0.240**●●	4.075 ± 0.261	3.995 ± 0.234*■■◆◆	F = 7.559 p = 0.003 η^2 = 0.419
First step length (m)	1.116 ± 0.090	1.084 ± 0.084*●	1.118 ± 0.075	1.087 ± 0.137*	1.115 ± 0.065	1.091 ± 0.095*■	F = 11.100 p = 0.006 η^2 = 0.595
First step flight time (s)	0.276 ± 0.042	0.245 ± 0.042**●	0.275 ± 0.051	0.251 ± 0.030*	0.276 ± 0.060	0.253 ± 0.081**■	F = 16.192 p = 0.515 η^2 = 0.607
First step ground contact time (s)	0.197 ± 0.024	0.186 ± 0.021**	0.200 ± 0.021	0.189 ± 0.048**	0.201 ± 0.027	0.189 ± 0.036**	F = 15.186 p = 0.478 η^2 = 0.591
Total time of the first step (s)	0.473 ± 0.027	0.431 ± 0.027**◆●●	0.475 ± 0.030	0.440 ± 0.024*■●	0.477 ± 0.044	0.442 ± 0.035**■■◆	F = 9.721 p = 0.001 η^2 = 0.826

*■ indicates a significant difference compared with CST at the 0.05 level; ◆ indicates a significant difference compared with PT at the 0.05 level; ● indicates a significant difference compared with ET at the 0.05 level; ■■ / ◆◆ / ●● indicate significant differences at the 0.01 level; * indicates a significant within-group difference before and after the intervention at the 0.05 level; ** indicates a significant within-group difference before and after the intervention at the 0.01 level*

Table 3. Differences in lower limb joint moment indices during the first step among different intervention groups.

Metrics	CST (n = 8)		PT (n = 8)		ET (n = 8)		Group * Test session interaction effect
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	
Maximum hip joint torque (Nm/kg)	2.650 ± 0.273	5.783 ± 0.347**●●◆	2.821 ± 0.401	4.245 ± 0.563**■●	2.467 ± 0.507	3.163 ± 0.600**■■◆	F = 10.391 p = 0.001 η^2 = 0.497
Maximum knee joint torque (Nm/kg)	1.883 ± 0.378◆●●	2.177 ± 0.350*●●	2.260 ± 0.484■	2.389 ± 0.368●●	2.513 ± 0.516■■	3.056 ± 0.415**■■◆◆	F = 1.763 p = 0.196 η^2 = 0.144
Maximum ankle joint torque (Nm/kg)	0.077 ± 0.358	0.124 ± 0.437**◆	0.030 ± 0.547	0.056 ± 0.273■	0.095 ± 0.518	0.110 ± 0.511	F = 4.422 p = 0.025 η^2 = 0.396

*■ indicates a significant difference compared with CST at the 0.05 level; ◆ indicates a significant difference compared with PT at the 0.05 level; ● indicates a significant difference compared with ET at the 0.05 level; ■■ / ◆◆ / ●● indicate significant differences at the 0.01 level; * indicates a significant within-group difference before and after the intervention at the 0.05 level; ** indicates a significant within-group difference before and after the intervention at the 0.01 level*

Table 4. Differences in lower limb joint performance indicators during the first step among different intervention groups.

Metrics	CST (n = 8)		PT (n = 8)		ET (n = 8)		Group * Test session interaction effect
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	
Hip joint positive work (J/kg)	1.277 ± 0.223	0.529 ± 0.141**●●	0.935 ± 0.257	0.435 ± 0.086**●	1.086 ± 0.300	0.330 ± 0.105**■■◆	F = 0.972 $p = 0.395$ $\eta^2 = 0.085$
Knee joint positive work (J/kg)	0.578 ± 0.289●●	1.104 ± 0.251**●●	0.786 ± 0.225●●	1.218 ± 0.108**●	0.591 ± 0.285■■◆◆	1.513 ± 0.290**■■◆	F = 1.650 $p = 0.216$ $\eta^2 = 0.136$
Ankle joint positive work (J/kg)	1.055 ± 0.235	1.062 ± 0.179●	0.899 ± 0.251●	0.916 ± 0.161	1.174 ± 0.228◆	0.879 ± 0.154**■	F = 5.891 $p = 0.009$ $\eta^2 = 0.559$
Hip joint negative work (J/kg)	−0.290 ± 0.263●●	−0.991 ± 0.149**●●	−0.235 ± 0.192●●	−1.182 ± 0.139**●	−0.313 ± 0.379■■◆◆	−0.653 ± 0.180**■■◆	F = 1.243 $p = 0.009$ $\eta^2 = 0.406$
Knee joint negative work (J/kg)	−0.121 ± 0.058●●	−0.027 ± 0.021**◆	−0.105 ± 0.061●●	−0.011 ± 0.042**■●●	−0.099 ± 0.088■■◆◆	−0.040 ± 0.041*◆◆	F = 13.192 $p = 0.000$ $\eta^2 = 0.557$
Ankle joint negative work (J/kg)	−0.429 ± 0.170	−0.389 ± 0.086	−0.450 ± 0.035	−0.337 ± 0.074*	−0.478 ± 0.122	−0.346 ± 0.092*	F = 0.788 $p = 0.468$ $\eta^2 = 0.070$

*■ indicates a significant difference compared with CST at the 0.05 level; ◆ indicates a significant difference compared with PT at the 0.05 level; ● indicates a significant difference compared with ET at the 0.05 level; ■■ / ◆◆ / ●● indicate significant differences at the 0.01 level; * indicates a significant within-group difference before and after the intervention at the 0.05 level; ** indicates a significant within-group difference before and after the intervention at the 0.01 level*

Table 5. Differences in lower limb stiffness indices during the first step among different intervention groups.

Metrics	CST (n = 8)		PT (n = 8)		ET (n = 8)		Group * Test session interaction effect
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	
Hip joint stiffness (N·m·kg^{-1}/°)	0.102 ± 0.027●	0.087 ± 0.010*	0.095 ± 0.026	0.084 ± 0.009●	0.081 ± 0.019■	0.098 ± 0.011*◆	F = 4.388 $p = 0.026$ $\eta^2 = 0.695$
Knee joint stiffness (N·m·kg^{-1}/°)	0.056 ± 0.016◆	0.052 ± 0.008●●	0.072 ± 0.018■●●	0.051 ± 0.004**●●	0.049 ± 0.010◆◆	0.065 ± 0.007**■■◆◆	F = 14.507 $p = 0.000$ $\eta^2 = 0.580$
Ankle joint stiffness (N·m·kg^{-1}/°)	0.058 ± 0.009	0.078 ± 0.004**●	0.060 ± 0.011	0.068 ± 0.002*	0.060 ± 0.013	0.065 ± 0.005■	F = 2.477 $p = 0.000$ $\eta^2 = 0.491$

*■ indicates a significant difference compared with CST at the 0.05 level; ◆ indicates a significant difference compared with PT at the 0.05 level; ● indicates a significant difference compared with ET at the 0.05 level; ■■ / ◆◆ / ●● indicate significant differences at the 0.01 level; * indicates a significant within-group difference before and after the intervention at the 0.05 level; ** indicates a significant within-group difference before and after the intervention at the 0.01 level*

Table 6. Differences in vertical ground reaction force indices during the first step among different intervention groups.

Metrics	CST (n = 8)		PT (n = 8)		ET (n = 8)		Group * Test session interaction effect
	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	
vGRF1 peak time (s)	0.113 ± 0.023◆	0.108 ± 0.017	0.088 ± 0.016■●●	0.103 ± 0.012*	0.130 ± 0.009◆◆	0.107 ± 0.014*	F = 3.923 $p = 0.043$ $\eta^2 = 0.343$
vGRF2 peak time (s)	1.157 ± 0.125	0.957 ± 0.041**	1.143 ± 0.176	0.963 ± 0.146**	1.137 ± 0.205	1.077 ± 0.103	F = 0.283 $p = 0.757$ $\eta^2 = 0.026$
vGRF1 peak value (BW)	696.783 ± 238.28	660.072 ± 208.193	655.832 ± 231.16	657.223 ± 276.489	779.291 ± 205.578	708.553 ± 194.033	F = 0.258 $p = 0.775$ $\eta^2 = 0.024$
vGRF2 peak value (BW)	1396.513 ± 105.001	1467.775 ± 103.391*●	1417.508 ± 164.179	1396.828 ± 128.946	1402.185 ± 122.677	1366.920 ± 94.820*■	F = 7.330 $p = 0.006$ $\eta^2 = 0.494$
apGRF peak value (BW)	136.225 ± 14.420	171.578 ± 17.357**◆●	144.458 ± 18.888	162.227 ± 21.102*■	148.366 ± 19.032	164.316 ± 16.405*■	F = 6.467 $p = 0.019$ $\eta^2 = 0.391$

*■ indicates a significant difference compared with CST at the 0.05 level; ◆ indicates a significant difference compared with PT at the 0.05 level; ● indicates a significant difference compared with ET at the 0.05 level; ■■ / ◆◆ / ●● indicate significant differences at the 0.01 level; * indicates a significant within-group difference before and after training at the 0.05 level; ** indicates a significant within-group difference before and after training at the 0.01 level*

Discussion

Targeted specialized strength training is crucial for helping sprinters master starting techniques and enhance initial acceleration (Jiang and Li, 2017). Compared with other training methods, resistance strength training with loads effectively meets the flexion and extension strength requirements of the hip, knee, and ankle joints in sprinting (Xu, 2000). Consequently, it has been widely adopted in specialized strength training for sprinters.

During the first and second steps after leaving the starting block, athletes should avoid taking excessively long strides to prevent a premature rise in their center of mass, which could negatively affect acceleration (Jiang et al., 2016). Therefore, during the acceleration phase of the start, the goal should be to maximize step frequency throughout the starting process (Mann and Murphy, 2015). In this study, the interaction effect exhibited a substantial effect size. The CST group demonstrated the greatest improvement in 30-m performance, with participants showing a significant reduction in both ground contact time and flight time during the first step, leading to a marked increase in step frequency. The results revealed a highly significant improvement in GRF and joint stiffness following CST, indicating enhanced acceleration capability and faster reaction time for sprint athletes.

Furthermore, the total time for the first step in the CST group was significantly different compared with that in the other two training groups (PT and ET). The interaction effect exhibited a large effect size, underscoring the robust effect of CST on reducing total first-step time.

Moreover, stride length was slightly shortened, likely attributable to the increase in step frequency resulting from shorter ground contact times, reduced vertical displacement of the center of mass, and consequently shorter stride length (Brazil et al., 2017).

Joint torque reflects the magnitude of muscle strength (de Koning et al., 1992). Among the key elements of energy production in the body, hip power generation is the most critical because it determines the energy input required for the swinging leg during the support phase. All three training methods significantly increased hip joint torque during the first step of landing, demonstrating their effectiveness in improving the strength of the hip joint-associated muscle groups. Notably, the CST group exhibited the greatest improvement, with the interaction effect showing a large effect size. This substantial effect size highlights the robust effect of CST on hip joint torque, demonstrating its superior efficacy in improving both muscular strength and functional performance. CST combines high-intensity strength training with high-velocity training, enhancing both strength and speed (Baker and Newton, 2005; Pereira et al, 2025).

The findings of this study align with those of Bret et al. (2002) and Kalkhoven and Watsford (2017), which suggest that lower-limb joint stiffness, particularly ankle joint stiffness during the first step at the start of a sprint, critically affects acceleration-phase performance. Increases in lower-limb joint stiffness reduce ground contact time and enhance the frequency of running and jumping movements. Greater muscle strength has also been shown to increase joint stiffness.

In this study, CST significantly improved ankle joint stiffness, with the interaction effect exhibiting a large effect size. This substantial effect size underscores the robust effect of CST on enhancing ankle joint stiffness, demonstrating its effectiveness in optimizing biomechanical efficiency. CST can fully utilize the stretch-shortening cycle in plyometric exercises, enhancing athletes' rapid transition from eccentric to concentric muscle contractions and shortening ground contact time.

The peak vGRF2 indicates the magnitude of the force exerted by the body on the ground during the landing phase, which is closely related to lower-limb maximum strength and explosiveness. In this study, CST significantly enhanced peak vGRF2 during the first-step landing phase, generating greater external force and showing significant differences compared with the other two groups. The interaction effect exhibited a large effect size, highlighting the robust effect of CST on improving peak vGRF2. This finding supports Morin et al.'s (2012) conclusion that elite athletes maximize acceleration and sprint speed by exerting greater force on the ground.

This study also reveals that all three training methods effectively improved peak apGRF during the first step at the start of a sprint, with CST yielding the most significant enhancement. The interaction effect demonstrated a large effect size, highlighting the robust effect of CST on apGRF enhancement. The greater horizontal forces generated during the first step resulted in a substantial improvement in resultant acceleration.

Conclusions

CST is more beneficial than PT and ET in improving step frequency, peak GRF, lower-limb joint torque, and lower-limb joint stiffness during the first step during the start of a sprint. Although this study evaluated short-term (8-week) adaptations, subsequent research should investigate the long-term effects (e.g., over months or years) of CST training on sprint mechanics and injury rates. A range of set and repetition schemes should also be explored (e.g., 4 × 8 vs. 5 × 5). Moreover, sprinters are advised to incorporate CST into their specialized strength training, particularly when aiming to improve the acceleration phase at the start of a sprint.

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